Plasma convection near the magnetic null of a snowflake divertor

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Contributions of V. Soukhanovskii and TCV group are gratefully acknowledged

Snowflake divertor employs a significant change of the magnetic field geometry in the divertor area

Other novel divertors based on geometrical effects:

An X-divertor: magnetic flux flaring at both strike points (e.g., M. Kotschenreuther, P.M. Valanju, S.M. Mahajan, J.C. Wiley, Phys. Plas, **14** 072502, 2007)

A Super-X divertor: increasing the major radius of the outer strike point (e.g., P.M. Valanju, M. Kotschenreuther, S.M. Mahajan, J. Canik, Phys. Plas, **16**, 056110, 2009)

In this paper we consider the effect of the SF geometry on the heat loads *during* the ELM event

In the previous work* it was conjectured that, in the ITER-scale facilities one can expect a roughly order-of-magnitude decrease of the surface heating in the SF geometry vs the "standard" one

Here we focus on one aspect of the heat-load mitigation effect, that of the plasma convection in the null-point zone

* D.D. Ryutov, T.D. Rognlien. "Using the snowflake geometry to mitigate pulsed divertor heat loads during ELM events," Paper 3O3 presented at the Sherwood Fusion Theory Conference, Austin, TX, May 2-4 2011.

OUTLINE

General properties of the snowflake (SF) divertor

Possible control over ELMs (their amplitude, their frequency, their total elimination…)

Possible mitigation of the pulsed divertor heat loads once ELM occurred:

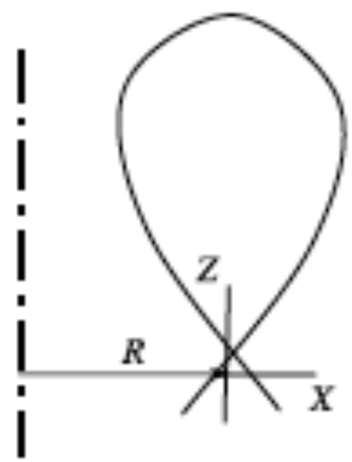
- Longer connection length
- A push-back effect
- Broader imprint
- Splitting of the heat flux between 4 strike points

Summary

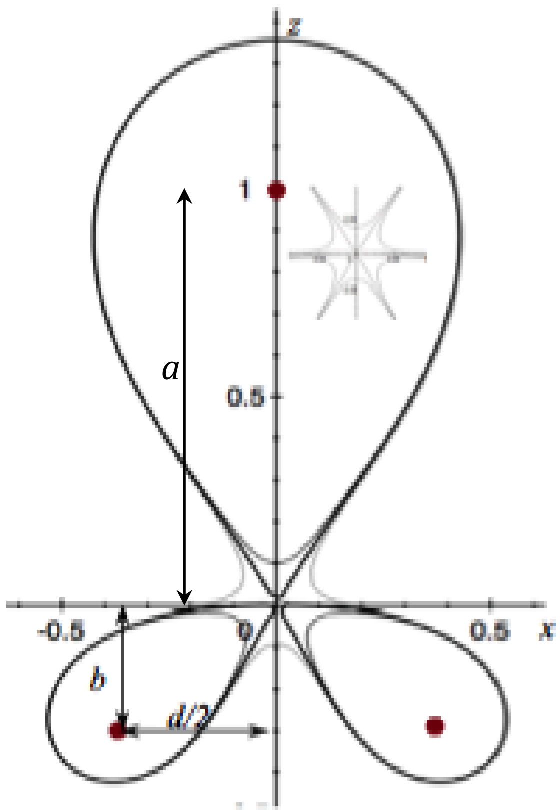
We are *not* attempting to predict the ELMs occurrence and their parameters.

We rather discuss the processes that occur *after* a certain amount of energy is dumped into the edge plasma.

We look into the issue of what is then happening to that energy and how it is distributed between the strike points.



A snowflake divertor: not only B_p but also its first spatial derivative are zero at the null-point ($B_p \sim r^2$ vs $B_p \sim r$ in the standard case)



Snowflake divertor in symmetric 3-wire configuration.

Two conditions must be satisfied:

$$I_d = I_{d0} \equiv I\frac{2b}{a-b};\ d = 2b\sqrt{\frac{a+b}{a-b}}.$$

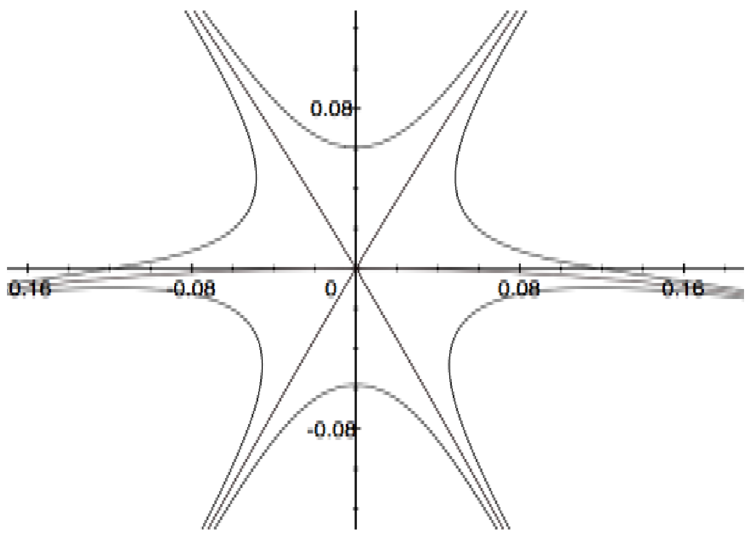
For $b=0.3a$, the total current in both divertor coils is $I_d=0.9I$. For a=5m, the divertor coils are situated at a distance 2.5 m from the null point

Divertor coils can be situated outside TF coils!

D.D. Ryutov. Phys. Plas, **14**, 064502, 2007

Attractive features of the snowflake configuration

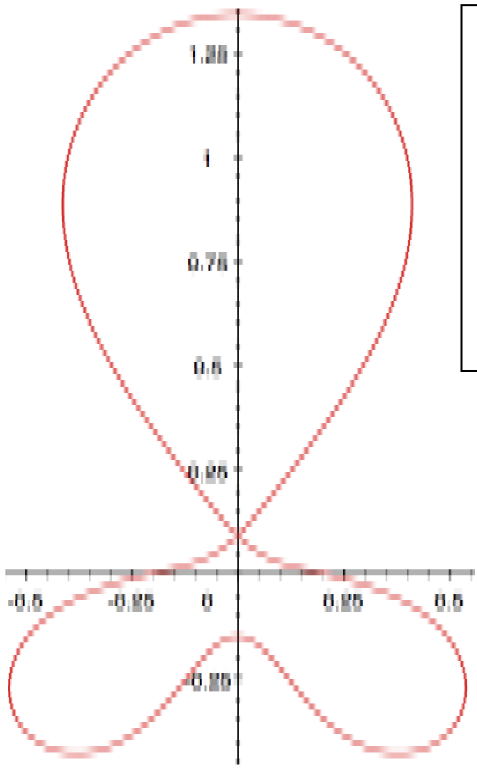
- Larger flux-expansion ratio
- Increased magnetic shear in the pedestal region (potentially better control of ELMs)
- Control over blob transport (stronger flux-tube squeezing near the null-point)
- Increased connection length
- Increased non-quasineutral ion transport, leading to stronger shear flows in the pedestal region
- Possibility to create this configuration with existing set of PF coils on existing devices (DIII-D, NSTX, TCV….)
- Possibility to create “snowflake” in ITER-scale machines with PF coils situated outside TF coils



D.D. Ryutov, R.H. Cohen, T.D. Rognlien, M.V. Umansky. Phys. Plasmas, **15**, 092501 (2008)

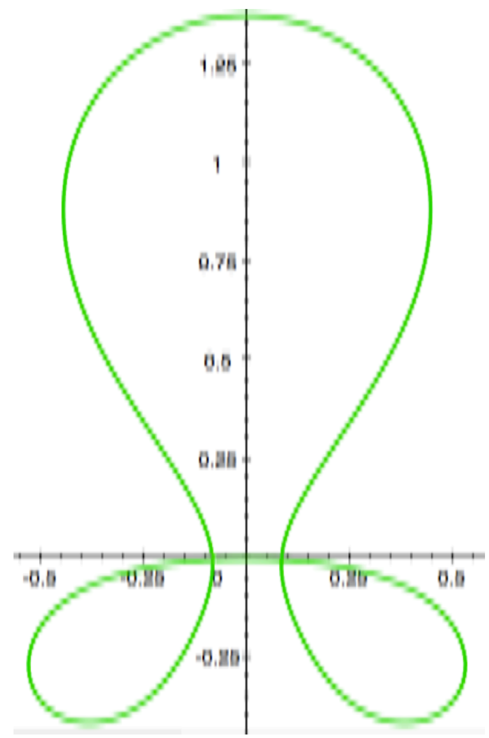
A problem: the *exact* snowflake configuration is topologically unstable

The configuration becomes either an X-point configuration (if the divertor current is higher than needed), or a double-X-point configuration (if the divertor current is lower than needed).



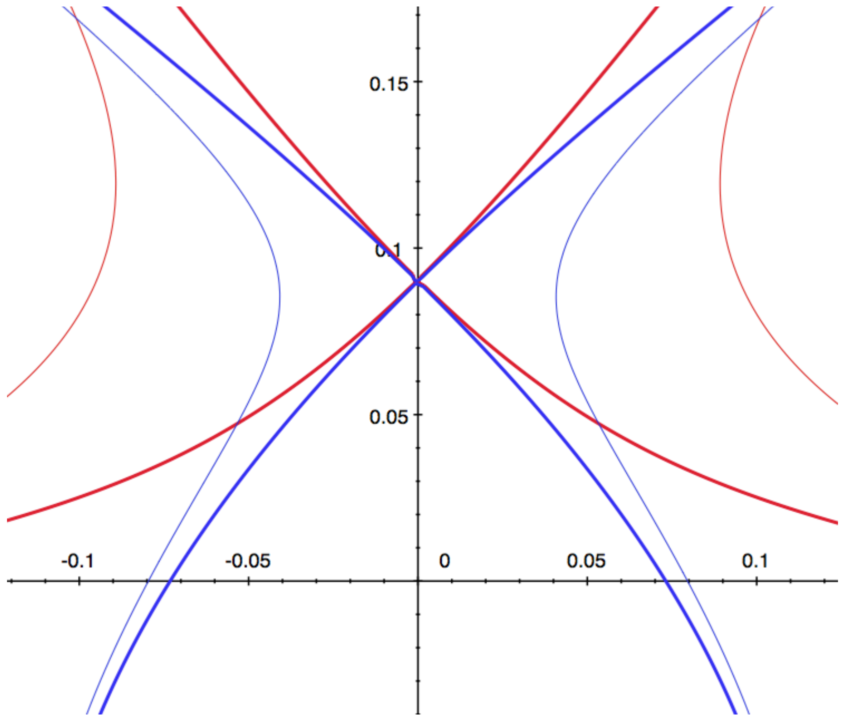
The divertor current is 5% higher than I_{d0}. We call this configuration "snowflake-plus"

The divertor current is 5% lower than I_{d0}. We call this configuration "snowflake-minus"

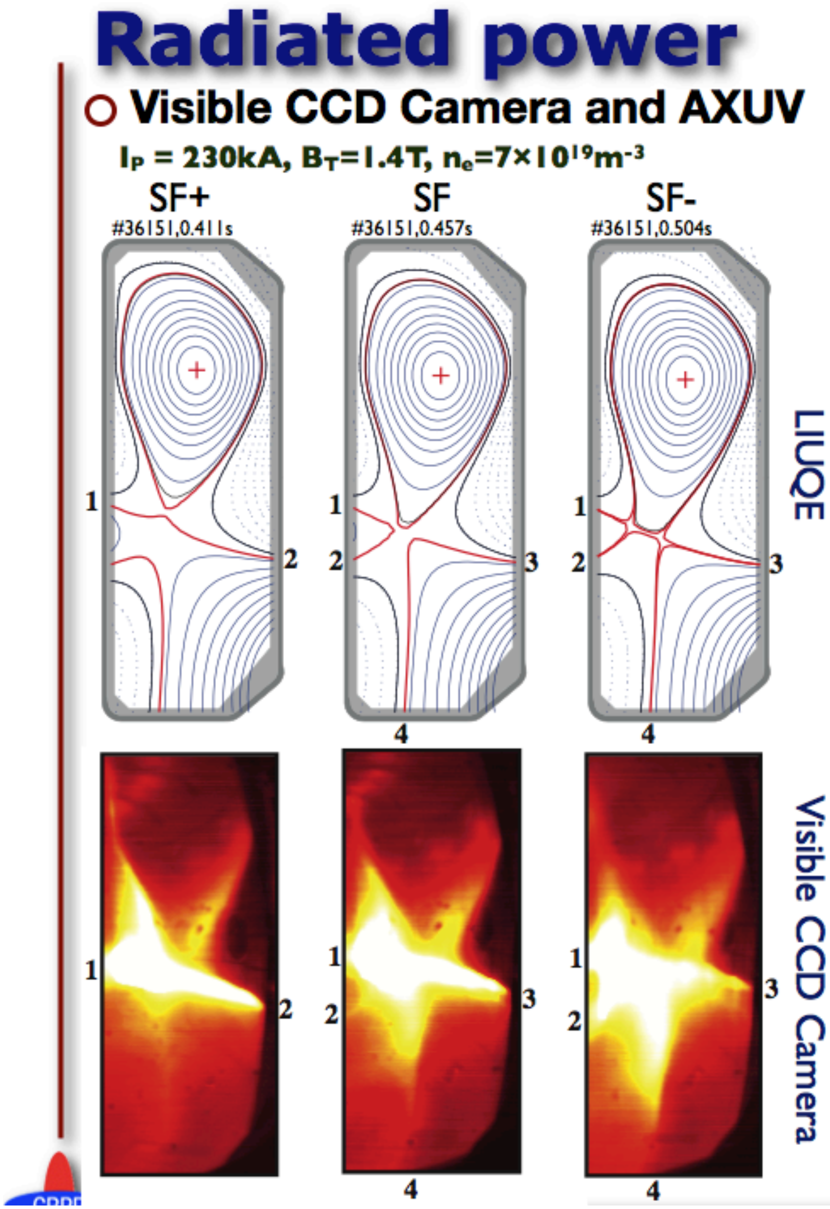


The "plus" and "minus" configurations are remarkably robust for $|\varepsilon|$ as low as 0.02, $I_d = I_{d0}(1+\varepsilon)$

Comparison of the SOL geometry near the null point in the snowflake-plus divertor (red lines) and a standard X-point divertor (blue lines).



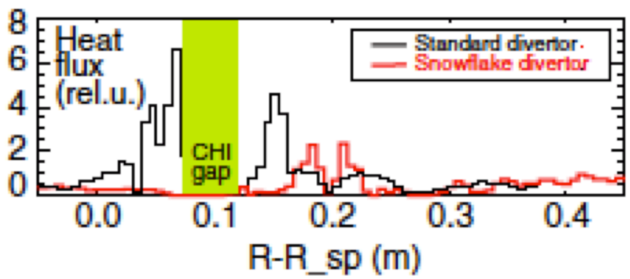
The flux expansion is 2-3 times higher for the snowfake-plus configuration (ε=0.05)



Piras F, Coda S, Furno I, Moret JM, Pitts RA, Sauter O, Tal B, Turri G, Bencze A, Duval BP, Felici F, Pochelon A, Zucca. “Snowflake divertor plasmas on TCV”, *Plasma Physics And Controlled Fusion,* **51,** 055009, 2009,

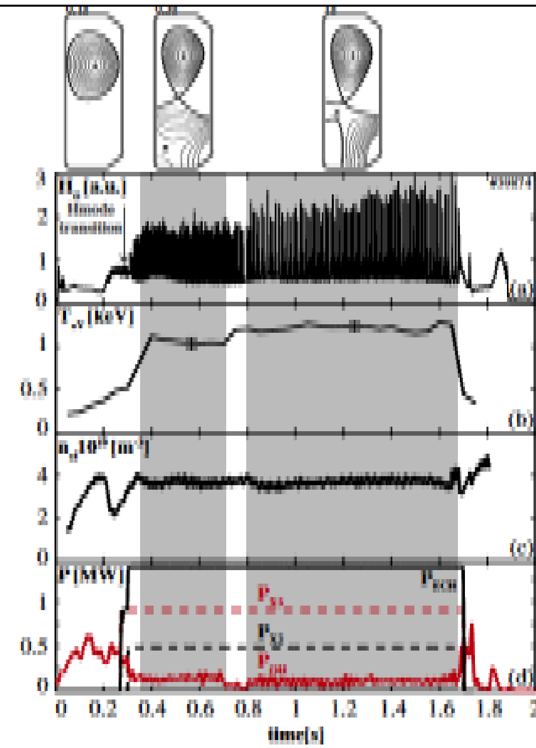
Encouraging results from two tokamaks: NSTX and TCV

NSTX: factor of 3 heat-flux reduction on the divertor plate (V.A. Soukhanovskii et al, Nucl. Fusion, **51**, 012001, 2011)



Easier detachment (no need for gas puff)
Carbon content in the core down by a factor ~ 2
Radiation from the core down by a factor ~ 2
Radiation from divertor up by a factor of a few
No noticeable adverse effect on core plasma density and temperature

TCV: strong effect on ELMs (F. Piras et al, PRL, **105**, 15503, 2010)



Theory: M.V. Umansky et al, CPP, 50, 350, 2010; Medvedev et al, CPP, 50, 324, 2010; D.D. Ryutov, M.V. Umansky, Phys. Plas, **17**, 014501, 2010

Potential beneficial effects of a snowflake during an ELM event

The connection length $L_{//}$ in a snowflake increases significantly compared to the standard divertor (~3-4 times for an ITER-scale facility). This may slow down the heat release from the mid-plane SOL to the divertor plate and increase the instantaneous pressure in the midplane SOL.

The pressure increase in the SOL should have a push-back effect on the very instability that generates ELMs: the duration of the energy release t_0 would increase with $L_{//}$, from the standard null to the snowflake.

Strong convection arising near the null-point splits the heat load between several strike points (4 instead of 1 or 2) and broadens the wetted area

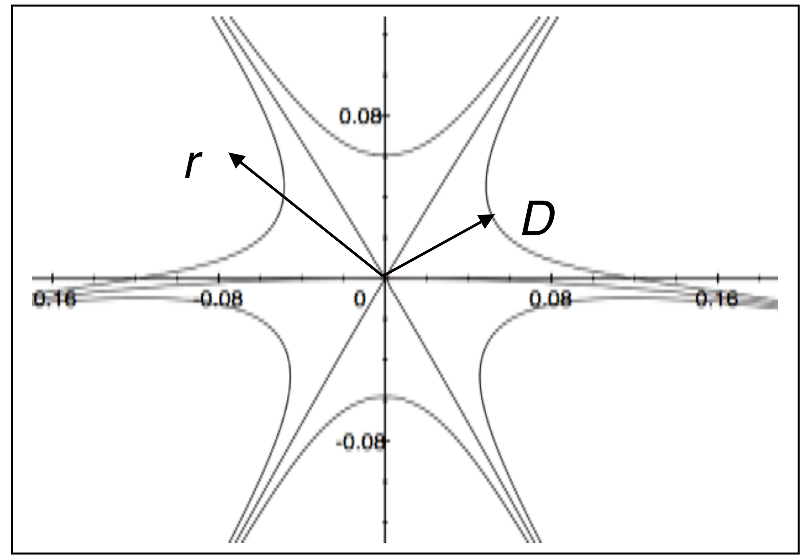
Some geometric relations

The poloidal magnetic field strength near the null-point:

$$B_p \sim B_{pm} (r/a)^2$$

The minimum distance D of a flux surface from the null point vs the distance d of this flux surface from the separatrix in the midplane:

$$D \sim a(d/a)^{1/3} \text{ [or } d \sim a(D/a)^3\text{]}$$



The connection length to the vicinity of the null-point:

$$L \sim 2\pi R(B_T/B_{pm})(a/d)^{1/3}$$

The sequence of events during the ELM:

The SOL is suddenly populated with denser, hotter plasma

The plasma streams to the divertor region, filling the low PF zone near the null-point

The poloidal beta in this zone jumps up to the values exceeding 1

Convection driven by the toroidal curvature begins and causes spreading of the plasma between all four strike points and broadening of the vetted area.

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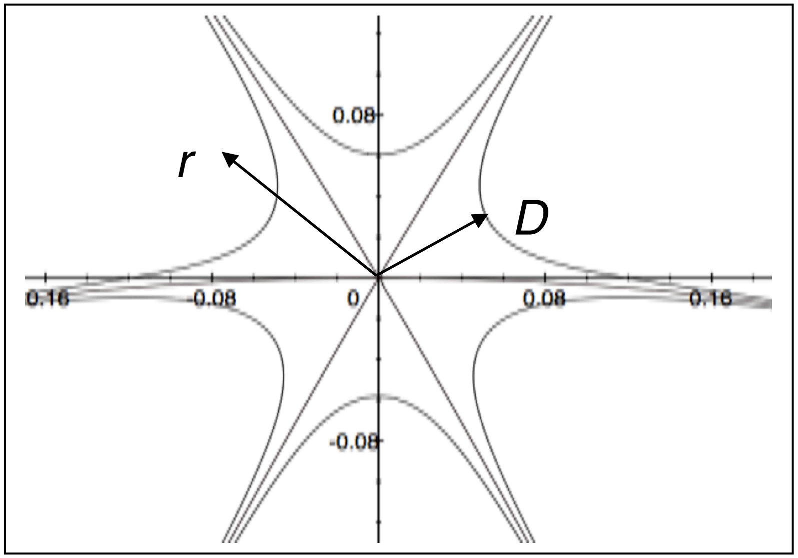

The connection length to the vicinity of the null-point:

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The poloidal beta at the distance *D* from the null:

$$\beta_p \sim \beta_{pm}(a/d)^{4/3}$$

The curvature-driven convection is intense

Turn-over time

$\tau_{conv} \sim (\rho R/|p'|)^{1/2} \sim (DR)^{1/2}/c_s \sim (aR)^{1/2}(d/a)^{1/6}/c_s$

Parallel flow time

$\tau_{||} \sim L/c_s$

The second is longer than the first, meaning that, during the ELM event, the heat flux is distributed evenly between 4 strike points.

Convection zone broadens, to reach the size where β_p becomes ~ 1. This means that the wetted area (projected to the midplane) reaches the width of $\sim a(\beta_{pm})^{3/4}$

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Predictions for the experimental tests: 1) characteristic frequency of convective motion; 2) strong (~1) fluctuations of the poloidal magnetic field; 3) the wetted zone width dependence on β_{pm}

A numerical example:

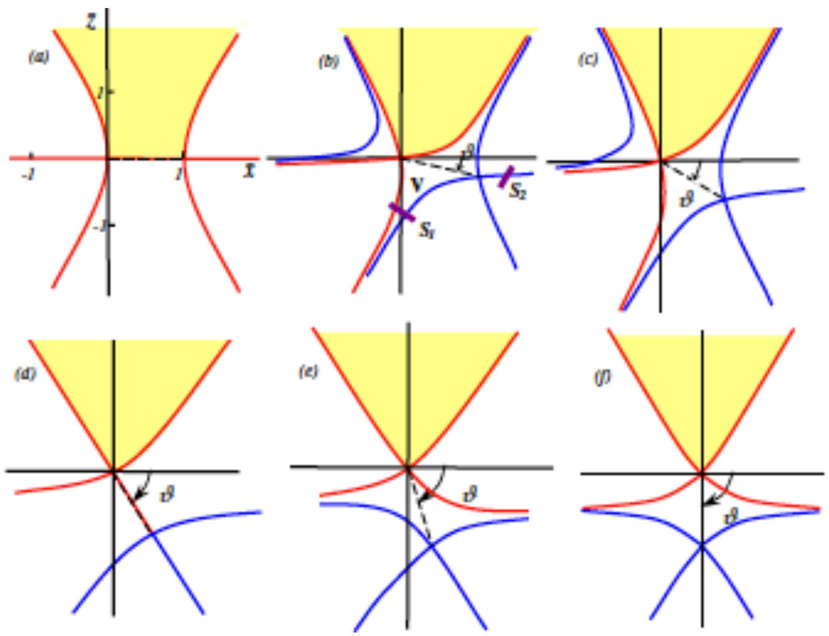
n=5×10^{13} cm^{-3}, T_e+T_i=100 eV, B_{pm}=0.8 T, β_{pm}=1.5×10^{-3},

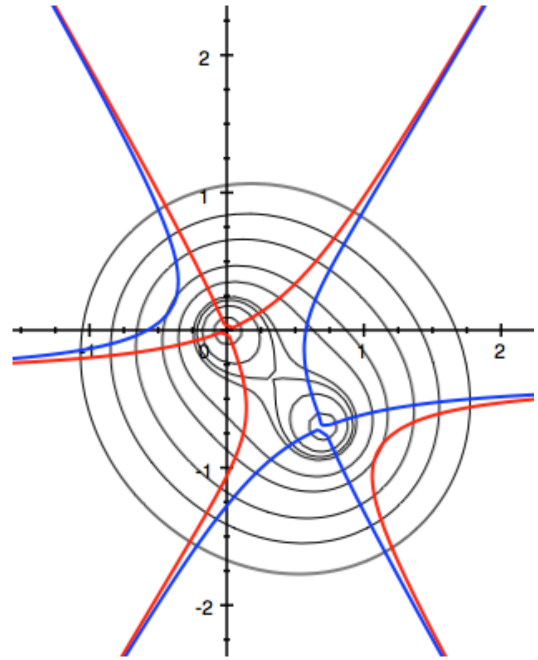
R=500 cm, a=200 cm, d=1 cm

Then,

τ_{conv}=20 μs, $\tau_{//}$=500 μs, wetted zone width $a(\beta_{\mathrm{pm}})^{3/4}$~1.5 cm

This conclusion holds for all “near-snowflake” configurations provided the distance between the nulls is smaller than r_{conv}





modB_p contours for an asymmetric SF.

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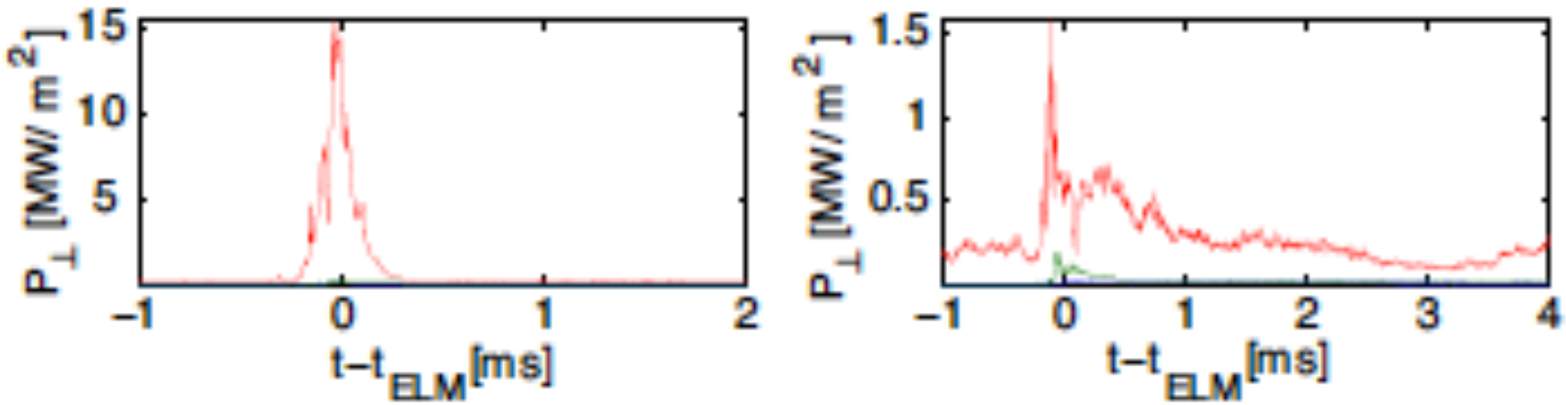
Total reduction of the surface temperature rise during the ELM event ~ 10

Recent dedicated TCV experiments (B. Labit et al, 2011 EPS Conference, P2.076) show that this may actually be true



SUMMARY

In the snowflake configuration the heat loads on the divertor plates will be significantly reduced compared to the standard X-point divertor (provided the ELM energy release and duration are comparable for both cases)

The favorable effect is caused by several factors, among which the most significant ones are the increased connection length and the presence of a highly convective zone near the null-point

The ease at which the change from the standard to a snowflake configuration is done in the existing facilities, can make a comparative study of ELMs a very helpful research tool in the development of a better understanding of the edge physics

BACKUP SLIDES

An X-divertor: flaring-up magnetic flux in both strike points (e.g., M. Kotschenreuther, P.M. Valanju, S.M. Mahajan, J.C. Wiley, Phys. Plas, **14** 072502, 2007)

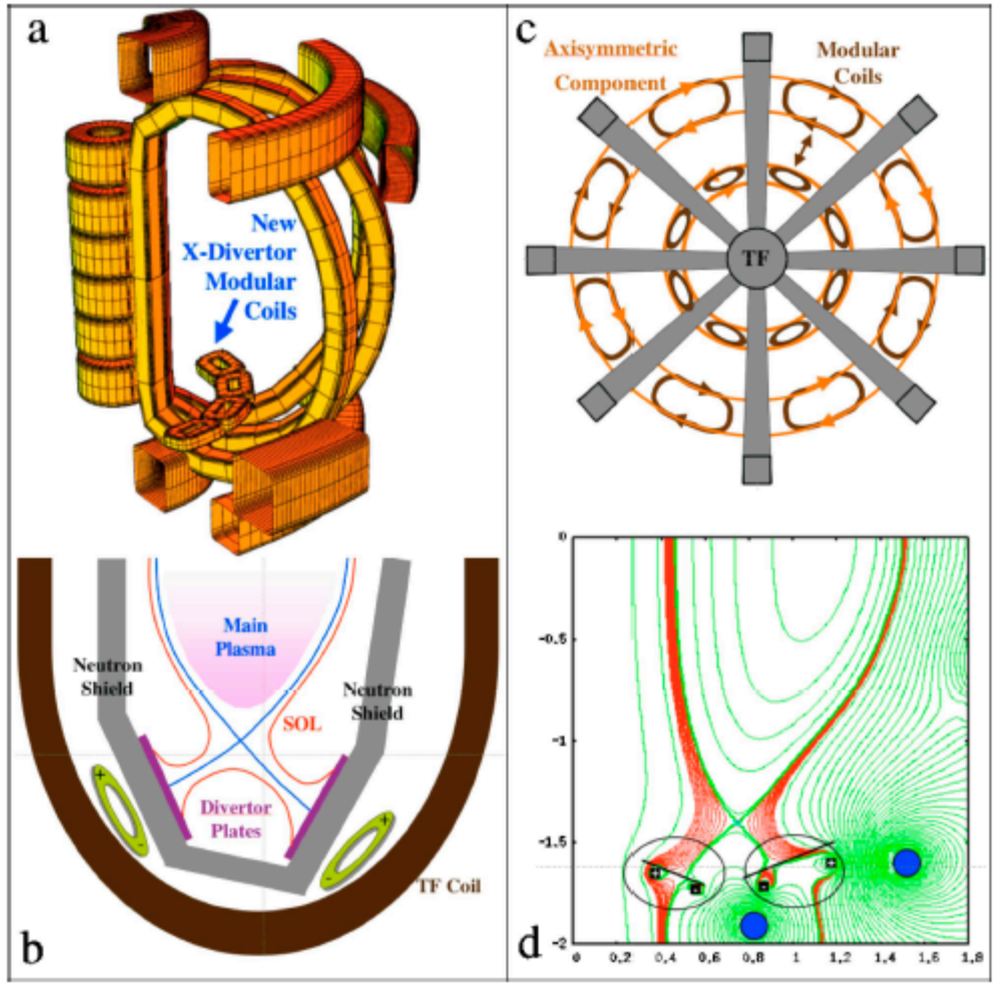


FIG. 3. (Color online) (a) Modular X-divertor (XD) coil loops (which can be rectangular). Note that the plasma *does not go through the loops*—the loops are behind the divertor plates (these are not bundle divertors). (b) Side view. Modular coils are behind neutron shield. (c) The axisymmetric component of the currents in the loops is equivalent to the axisymmetric poloidal coils (+ and −) with opposite currents. Only eight TF coils are shown in this top view for clarity. (d) Flux expansion (see encircled areas) in NSTX MHD equilibrium calculated using the code FBEQ.[36]

A Super-X divertor: increasing the major radius of the outer strike point (e.g., P.M. Valanju, M. Kotschenreuther, S.M. Mahajan, J. Canik, Phys. Plas, **16**, 056110, 2009)